

Electrical Manipulation of Nanomagnets

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We demonstrate a possibility to manipulate the magnetic coupling between two nanomagnets with a help of ac electric field. In the scheme suggested the magnetic coupling in question is mediated by a magnetic particle contacting with both of the nanomagnets through the tunnel barriers. The electric field providing a successive suppression of the barriers leads to pumping of magnetization through the mediating particle. Time dependent dynamics of the particle magnetization allows to switch between ferro- and antiferromagnetic couplings.

The sensitivity of electron transport to the spin degree of freedom brings new possibilities for implementing device functions in electronics. As a result the field of spintronics is developing rapidly. The giant magnetoresistance [1] is a striking example of an effect of spin dependent transport that has already found important applications in computer hardware. More fundamental ideas for using spin in order to realize devices that can store and process quantum information are now under intensive discussion in the literature [2,3].

Manipulation of the electron spin is only possible if one is able to control the magnetization of the magnetic materials that are necessary elements of any spintronics device. In nanoscale devices a fundamental obstacle to achieve the required level of control comes from the fact that the magnetic fields used to control the magnetization cannot be localized on the nanometer length scale. This is in sharp contrast to the electric fields used in modern nanoelectronics based on the Single-Electron devices [4]. The problem of selective control of the magnetization has therefore become crucial for functioning of the nanoscale spintronics devices. A use of electric rather than magnetic fields to manipulate nanomagnets could, if it works, be a way out of this “nonlocality trap”. A natural way to realize such a control is to make use of the indirect exchange interaction between nanomagnets induced by conducting electrons. Indeed, in the hybrid structures where ferromagnetic layers are separated by normal metals the indirect exchange can be controlled electrically by affecting the wave functions of electrons mediating the exchange [5,?,?]. In this case the transfer of spin polarization between the ferromagnetic layers is controlled by an interference pattern produced by different electronic waves and therefore crucially affected by any kind of structural material disorder. Since the latter is obviously dependent on the atomic scale details of interface geometry, the phenomenon becomes very sensitive to fluctuations and noise in the system.

The main idea of the present paper is to explore a new

possibility of magnetic coupling where a magnetization is transferred through some “time domains” rather than through the spatial domains. Such a possibility occurs if magnetic coupling between two nanomagnets is mediated by a small magnetic particle (“mediator”). Accumulation of magnetization transferred from one nanomagnet to another in an “intermediate state” on mediator enables one to realize a delay line with the possibility to control a magnitude and orientation of transferred magnetization. Electrical manipulation of nanomagnets becomes possible if exchange interaction, which is essentially of electrostatic origin, is employed.

A sketch of the structure to be considered is presented in Fig. 1.

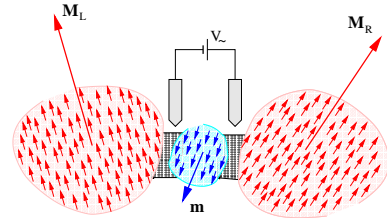


FIG. 1. Schematic diagram of the system discussed in the text. Single domain magnetic grains with magnetic moments \mathbf{M}_L and \mathbf{M}_R are coupled via the magnetic cluster with magnetic moment \mathbf{m} , the latter being separated from the grains by insulating layers. The gate electrodes induce an ac electric field, concentrated in the insulating regions. This field controlling the heights of the tunnel barriers affects the exchange magnetic coupling between different components of the system.

The figure shows two single-domain nanomagnets with magnetic moments \mathbf{M}_L and \mathbf{M}_R . They are both coupled by the direct exchange interaction spreading through the corresponding tunnel barriers to a magnetic cluster or

magnetic molecule with the magnetic moment \mathbf{m} . So the cluster/molecule acts as a magnetic weak link between the magnets. An indirect exchange interaction between the two nanomagnets is mediated by the cluster/molecule which acts as a magnetic weak link between the magnets. Note that the exchange coupling between mediator and the magnetic leads is controlled by the heights of the tunnel barriers that separate the electronic states of the nanomagnets and the cluster. We will show that a periodic electric field applied to the tunnel barriers (inducing a time-dependent exchange coupling) can transform the character of the mediated exchange between the nanomagnets from being ferromagnetic to antiferromagnetic one. We will assume that the exchange coupling between mediator and leads has a time dependence that corresponds to a sequential coupling of the mediator to first one of the magnetic leads and then to another one, in a periodically repeating pattern (the heights of the tunnel barriers oscillate with a phase shift of π). In this case three stages of the mediated coupling between the leads can be distinguished: 1) polarization of the mediator by one of the leads (while the mediator is essentially decoupled from the other one); 2) the internal dynamics of the free mediator (this occurs when the mediator is decoupled from both leads); 3) transfer of the induced magnetic polarization from the mediator to the second lead (while decoupled from the first one). For simplicity we will omit this step, assuming that there is no nontrivial dynamics of the mediator spin when decoupled from the leads. Under these conditions the time evolution of \mathbf{m} can be thought of as being due to a sequence of "scattering events". A single "scattering" results in a change of the mediator magnetic moment by the value $\Delta\mathbf{m}$. On the other hand, due to the conservation of magnetic momentum, a magnetic moment change takes place also in the lead after the "scattering" event. Therefore, one can look at the process as being the mediator-assisted flow of magnetic polarization between the leads. This flow, giving rise to a synchronized evolution of the magnetization in the leads, establishes an effective coupling between them.

Since $M \gg m$ the dynamics of the magnetization in the leads is much slower than the dynamics of the magnetic moment (spin) of the mediator. When considering the dynamics of the mediator magnetization, one can therefore to a first approximation neglect the variation of \mathbf{M} altogether. Thus the time-dependent exchange coupling of the mediator to the leads will result in an effective periodically oscillating magnetic field acting on the magnetic moment of the mediator. As we will prove below, any weak relaxation will bring the mediator magnetization $\mathbf{m}(t)$ into a periodic regime for which $\mathbf{m}(t) = \mathbf{m}(t + 2T)$. In this regime the magnetic moment of the mediator changes from a value \mathbf{m}_1 to another value \mathbf{m}_2 during a first half-period when the mediator cluster is coupled to the left lead, and vice versa (from \mathbf{m}_2 to

\mathbf{m}_1) during a second half-period when it is coupled to the right lead. While being coupling to a lead, the mediator being affected by an effective magnetic field with fixed direction and its moment rotates around an axis parallel to the magnetization of the lead (see Fig.2).

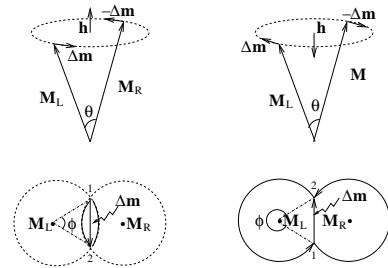


FIG. 2. Schematic diagram demonstrating the periodic dynamics of the projection of a mediator magnetization on the plane perpendicular to the vector $\mathbf{M}_L + \mathbf{M}_R$. Points L and R represent the axes aligned vectors \mathbf{M}_L and \mathbf{M}_R correspondingly. If molecular cluster is coupled to one of the nanomagnets, its magnetic moment rotates counter-clockwise around the axes L or R (depending on what nanomagnet it is subject to). The circles schematically represent the trajectories which are traced out by the end of the vector \mathbf{m} . The angle of rotation ϕ depends on the length of time interval during which the mediator is coupled to the nanomagnets and on the intensity of exchange coupling. The mediator magnetization evolution is matched to be the oscillations between points 1 and 2 after each half-period. Magnetic moment $\Delta\mathbf{m}$ is transferred from one nanomagnet to another one during the period setting them into rotational motion around axes $\mathbf{M}_L + \mathbf{M}_R$ (upper part of the figure).

The total angle of rotation $\phi_\alpha = g\bar{J}_\alpha M_\alpha T$, after the mediator has been magnetically coupled to the lead for a certain amount of time during one contact, depends on the average exchange coupling strength \bar{J}_α and the effective coupling time T ($g = 2\mu/\hbar$, μ is the Bohr magneton). One finds that in the symmetric case ($\phi_L = \phi_R = \phi$) that we will consider in this report the vector $\Delta\mathbf{m}$ is perpendicular to the plane spanned by \mathbf{M}_L and \mathbf{M}_R (below denoted the xy -plane). The flow of polarized magnetization will result in a rotation of \mathbf{M}_α around an axis parallel to the vector $\mathbf{M}_L + \mathbf{M}_R$ (below x -axes). It can be described as an effect of some magnetic field \mathbf{h} directed along that axes (see Fig.2). Relaxation processes, that are inevitably present, will tend to align the magnetization of the lead along this field. Let us suppose that the rotation angle $\phi = \phi_0$ is much smaller than 2π . Under this condition the vectors $\mathbf{m}_{1,2}$ will be aligned nearly along the bisector of the angle between \mathbf{M}_L and \mathbf{M}_R and therefore \mathbf{h} will be directed along the vector $\mathbf{M}_L + \mathbf{M}_R$. In such a case the magnetic moments of the leads, since they tend to be aligned along the effective magnetic field, will obey a ferromagnetic order ($\theta = 0$). Now let us assume that the rotation angle is $2\pi - \phi_0 > \pi$. One finds,

that if a rotation by an angle ϕ_0 around some axis gives rise to a change of the magnetic moment from \mathbf{m}_2 to \mathbf{m}_1 , the rotation around the same axis by the angle $2\pi - \phi_0$ will transform \mathbf{m}_1 into \mathbf{m}_2 . Therefore, the periodic evolution of $\mathbf{m}(t)$ will be established in the way that during the first half period (when the mediator is coupled to the right lead) its moment changes from \mathbf{m}_1 to \mathbf{m}_2 and vice versa during the second half period. So we will have the same magnetic flow, but in the opposite direction. Thus one concludes that the effective magnetic fields at ϕ_0 and at $2\pi - \phi_0$ will be pointing in opposite directions. Consequently, at $\phi = 2\pi - \phi_0$ the \mathbf{h} should be anti-parallel to the vector $\mathbf{M}_L + \mathbf{M}_R$ making the ferromagnetic ordering unstable. Below we will show that if $\phi > \pi$ the system exhibits an antiferromagnetic ordering. Therefore, by tuning the rotation angle ϕ — which depends on the amplitude and frequency of the alternating electric field — one can switch from ferromagnetic to antiferromagnetic coupling between the magnetizations in the leads. For a quantitative discussion of the phenomena outlined above, we will use Landau-Lifshits equations:

$$\frac{1}{g} \frac{d\mathbf{m}}{dt} = \left(\frac{\partial W}{\partial \mathbf{m}} \times \mathbf{m} \right) + \frac{\beta}{|\mathbf{m}|} (\mathbf{m} \times (\mathbf{m} \times \frac{\partial W}{\partial \mathbf{m}})) \quad (1)$$

$$\frac{1}{g} \frac{d\mathbf{M}_\alpha}{dt} = \left(\frac{\partial W}{\partial \mathbf{M}_\alpha} \times \mathbf{M}_\alpha \right) + \frac{\beta}{M} (\mathbf{M}_\alpha \times (\mathbf{M}_\alpha \times \frac{\partial W}{\partial \mathbf{M}_\alpha}))$$

Here $M = |\mathbf{M}_\alpha|$, $m = |\mathbf{m}|$ and magnetic energy of system W has a form:

$$W = - \sum_{\alpha=L,R} J_\alpha (\mathbf{M}_\alpha \mathbf{m}) \quad (2)$$

where $J_\alpha(t)$ describes a periodic (with the period $2T$) time-dependent exchange coupling between mediator and magnetic leads. In this paper we take $J_{L,R}(t) = \bar{J}(1 \pm \alpha(t))/2$ with $\alpha(t) = \text{sign}(\sin \pi t/T)$. The second terms in equations (1) describe the relaxation with relative characteristic frequency β . In what follows we will assume $\beta \ll 1$, (according to literature [8] β varies from 0.5 to 0.005 depending on magnetic material). In this case the dissipation only slightly affects the magnetization dynamics and non-trivial regimes can be expected. If $M \gg m$, the dynamics of molecular spin is much faster than the dynamics of leads magnetization, and one can use adiabatic approximation to analyze the behavior of the system. To do this we will calculate $\mathbf{m}(\mathbf{t})$ under assumption that the magnetization of the leads is fixed and then substitute it into the equation (2). Then averaging over the fast oscillation one obtains the following equation for \mathbf{M}^α :

$$\frac{1}{g} \frac{d\mathbf{M}_\alpha}{dt} = (\bar{\mathbf{h}}^\alpha \times \mathbf{M}_\alpha) + \frac{\beta}{M} (\mathbf{M}_\alpha \times (\mathbf{M}_\alpha \times \bar{\mathbf{h}}^\alpha)) \quad (3)$$

where the effective magnetic fields $\bar{\mathbf{h}}^\alpha$ are given by the relation $\bar{\mathbf{h}}^\alpha = (2T)^{-1} \int_0^{2T} dt J_\alpha(t) \mathbf{m}(\mathbf{t})$. Therefore the dynamics of the leads magnetization is controlled by average spin polarization of the mediator when it is coupled to

the lead. Integrating equation (1) over period, we obtain $\mathbf{m}(2T) - \mathbf{m}(0) = gT\{(\mathbf{M}_L \times \bar{\mathbf{h}}^L) + (\mathbf{M}_R \times \bar{\mathbf{h}}^R)\}$. It means that in the case of periodic evolution ($\mathbf{m}(2T) = \mathbf{m}(0)$) the average fields $\bar{\mathbf{h}}^{L,R}$ obey the relations $(\mathbf{M}_L \times \bar{\mathbf{h}}^L) = -(\mathbf{M}_R \times \bar{\mathbf{h}}^R)$. Taken scalar product of this relation with \mathbf{M}_α one can easily find that the projection of $\bar{\mathbf{h}}^\alpha$ on the axis perpendicular to $(\mathbf{M}^L, \mathbf{M}^R)$ -plane (below xy-plane) is equal to zero in the periodic regime. As a result, $\bar{\mathbf{h}}^\alpha$ may be presented as a linear combination of magnetizations $A\mathbf{M}^\alpha + \bar{L}\mathbf{M}^\beta$, where coefficient \bar{L} is some function of the angle θ between the vectors \mathbf{M}^L and \mathbf{M}^R . One can represent the magnetic fields through effective inter-leads interaction energy \mathcal{W} :

$$\bar{\mathbf{h}}^\alpha = - \frac{\delta \mathcal{W}}{\delta \mathbf{M}^\alpha}$$

The structure of the effective potential \mathcal{W} controls the type (ferromagnetic or antiferromagnetic) of the interaction between the nano-magnets. Making use of the fact that \mathcal{W} depends only on the angle θ , and consequently can be represented as a function of scalar product $(\mathbf{M}^L \cdot \mathbf{M}^R)$, one can prove the following relations: $(\mathbf{e}_z \cdot (\mathbf{M}^L \times \mathbf{h}^L)) = -(\mathbf{e}_z \cdot (\mathbf{M}^R \times \mathbf{h}^R)) = \partial \mathcal{W}(\theta) / \partial \theta$ (here we has chosen the z-axes along $(\mathbf{M}_R \times \mathbf{M}_L)$). Using this relations one obtains the equation for the time evolution of the angle θ :

$$\frac{M}{g} \frac{d\theta}{dt} = \beta \frac{\partial \mathcal{W}}{\partial \theta} \quad (4)$$

On the other hand, multiplying Eq. (1) by \mathbf{e}_z and integrating over the first half-period $(0, T)$, (when the molecular spin is coupled to the left lead), or over the second one $(T, 2T)$, (when it is coupled to the right lead), we obtain $\Delta m_z / T = g \partial \mathcal{W}(\theta) / \partial \theta$. Combining this relation with Eq. (5) one obtains the following equation describing time evolution of the angle θ :

$$\frac{1}{T} \Delta m_z = \left(\frac{M}{\beta} \right) \frac{d\theta}{dt} \quad (5)$$

The value $\Delta m_z / T \equiv \bar{j}$ has a simple physical interpretation: it gives the average flow of the z-component of magnetization between the leads, mediated by the periodic evolution of the mediator magnetization. As a result a mutual rotation of vectors \mathbf{M}_α around x-axis with the frequency $\Omega = \bar{j}/M$ takes place. To describe the fast dynamics of \mathbf{m} it is convenient to use the matrix representation. Let us introduce the (2×2) matrix $\hat{\rho}$ with the following properties: $\text{Tr} \hat{\rho} = 0$, $\text{Tr} \hat{\sigma}_i \hat{\rho} = 2m_i/m$, ($i=x,y,z$ and σ_i are Pauli matrixes). In this case first equation in (1) can be written in a form:

$$\dot{\hat{\rho}} = -i[\hat{\mathbf{H}}(t), \hat{\rho}] - \beta[\hat{\rho}, \hat{\rho}\hat{\mathbf{H}}] \quad (6)$$

where

$$\hat{\mathbf{H}}(t) = \frac{1}{2}gM\bar{J}e^{i\alpha(t)\theta\hat{\sigma}_z/4}\hat{\sigma}_xe^{-i\alpha(t)\theta\hat{\sigma}_z/4} \quad (7)$$

Here we took x-axis in xy-plane along the bisector of the angle between \mathbf{M}^L and \mathbf{M}^R . Since the "Hamiltonian" $\hat{\mathbf{H}}(t)$ is a periodic function of time, the solution of Eq. (6) can be expressed in terms of "quasienergy" states $|t, \pm\rangle$ defined by the equations:

$$\begin{aligned} i\frac{d}{dt}|t, \pm\rangle &= \hat{\mathbf{H}}(t)|t, \pm\rangle \\ |t + 2NT, \pm\rangle &= e^{\pm i\lambda N}|t, \pm\rangle \end{aligned} \quad (8)$$

In this representation the matrix $\hat{\rho}$ has a form:

$$\begin{aligned} \hat{\rho} &= \rho(t)(|t, +\rangle\langle +, t| - |t, -\rangle\langle -, t|) \\ &+ \tau(t)|t, +\rangle\langle -, t| + \tau^*(t)|t, -\rangle\langle +, t| \end{aligned} \quad (9)$$

with $\rho^2 + |\tau|^2 = 1$. For $\beta = 0$ Eq.(9) is a solution of Eq. (6) with ρ and τ being time independent. At $\beta \ll 1$ the coefficients ρ and τ are slow functions of time. The equation for their time evolution can be found by substituting of $\hat{\rho}(t)$ in Eq. (6) and averaging over the period. In the case when mediator is not coupled to both leads simultaneously, the states $|t, \pm\rangle$ may be found exactly and as a result we have the following equation for the $\rho(t)$:

$$\frac{d\rho}{dt} = \beta g \bar{J} M (1 - \rho^2) C(\theta, \phi) \cos \phi / 2 \quad (10)$$

where $C(\theta, \phi) = (1 - \sin^2 \phi / 2 \cos \theta / 2)^{-1/2} \cos \theta / 2$. From this equation it follows that the molecular spin relaxes to the periodic regime of evolution ($|\tau| \rightarrow 0$) and at this regime $\rho = \text{sign}(\cos \phi / 2)$.

Now we can calculate $\dot{j} = m(2T)^{-1} \text{Tr} \hat{\sigma}_z (\hat{\rho}(T) - \hat{\rho}(0))$. Making use of the relation (5) we obtain the following equation for the time evolution of the angle θ :

$$\frac{d\theta}{dt} = -\beta T^{-1} \frac{m}{M} \text{sign}(\cos \phi / 2) B(\theta, \phi) \sin \theta \quad (11)$$

where $B(\theta, \phi) = \sin^2(\phi) / |\sin \lambda|$. From this equation we can conclude that the relative magnetization of the leads depends on the ϕ - the angle of precession of molecular spin during the act of its coupling to the lead. If this angle corresponds to $(2\pi n, 2\pi(n+1))$ the mediated exchange interaction imposes the ferromagnetic ordering between single-domain nano-magnets. If $2\phi \in ((2n-1)\pi, 2n\pi)$ the angle θ increases and system demonstrates a trend to establish the antiferromagnetic ordering. However our analysis based on the adiabatic approximation breaks for the narrow interval of angle θ : $|\theta - \pi| \leq m/M \ll 1$. The angle $\phi = gMJ_0 e^A T$ where

$A = V/V_0$ is proportional to the amplitude of alternating electrostatic potential applied to the tunnel barriers. Therefore varying the amplitude of electrical field (or period of oscillation) one can switch magnetic ordering of the nanomagnets.

To conclude, we suggest a new type of the voltage controlled exchange coupling between the two nanomagnets when the coupling is mediated by a small magnetic particle coupled with the nanomagnets through the tunnel barriers. We demonstrated that the sequential periodic suppression of the tunnel barriers with a help of external electric field allow both ferromagnetic and antiferromagnetic order in the system. The switch between the two types of the order can be made by a variation of the parameters of the controlling ac voltage. Nanomechanical manipulation of nanomagnets is an alternative to the above electrical one if "shuttling of magnetization" is induced by mechanical modulation of tunnel barriers, similarly to recent experiments [9,10], where shuttling of electric charge [11] was observed.

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